

Correlation Model for Heat Release Rate of Lignocelulosic Materials in a Full Scale from Small Scale Experimental Data

¹M. Konecki, ¹J. Gałaj

¹Professor, Head of Fire Development and Extinguishing Department,
The Main School of Fire Service, Warsaw, Poland

²Assistant Professor, Head of Hydromechanics Division, The Main School of Fire Service,
Warsaw, Poland

Abstract: A method for determination of heat release rate (HRR) for lignocelulosic materials in a full scale based on the heat release data obtained from a small scale experiments is presented in this paper. It extends calculation possibilities of the existing models for the experimental correlations resulting from the relationship between HRR and area of the combustion zone. The applicability of the correlation functions for estimation of HRR in the selected fire models is also discussed in this work.

Key words: fire, heat release rate, cone calorimeter, experimental correlation model, model validation, zone fire modeling, hybrid fire modeling, full-scale test

INTRODUCTION

Heat release rate during combustion process is one of the most important input parameters in fire development models^[1]. It can be determined either directly during full-scale tests or based on the correlation between small-scale and full-scale experiments. Previous works on the experimental correlations^[2-6] showed that knowing a heat rate

$\dot{q}''(CC)$ emitted from 1 m² of a specific flammable material, estimated using cone calorimeter method^[7], and relationship of effective heat release surface

$A_{Q_{eff}} = A_{Q_{eff}}(t)$ obtained from the experimental correlations, function of the heat release rate from the material with time $\dot{Q} = \dot{Q}(t)$ in a full scale can be given. Therefore, in this work it has been assumed that the function $\dot{Q} = \dot{Q}(t)$ in a full scale test can be determined based on the heat release rate from the unit surface in a small scale test with cone calorimeter.

Messerschmidt *et.al.*^[3] and Hansen^[4,5] determined the experimental correlations between data from SBI (Single Burning Item)^[8] full-scale test and data from cone calorimeter small-scale test.

Correlation model presented by Messerschmidt^[3] is

applicable only to the first part of the curve \dot{Q} (300-400 s from the ignition point) for the SBI test. It allows to estimate the correct values of FIGRA parameter for 23 different materials. Whereas, model proposed by Hansen^[4] is an extended Messerschmidt's model valid for the whole time range of $\dot{Q} = \dot{Q}(t)$ curve.

Both models are based on the material dependent variable, so called effective heat release surface

$A_{Q_{eff}}$ from which the heat that is released \dot{q}'' is determined using the cone calorimeter method.

This paper presents an experimental correlations model to be used for estimation of HRR from the lignocelulosic materials in a full scale fire, using experimental data from a small scale experiments with cone calorimeter.

The Correlation Model: The main assumptions made in the model:

1. The material to be burned is placed vertically to the floor. Spread of flame is possible along both sides of the flammable material, which thermo-physical properties are independent on the temperature.

Corresponding Author: M. Konecki, Assistant Professor, Head of Fire Development and Extinguishing Department, The Main School of Fire Service, Warsaw, Poland.
E-mail: mkonec@sgsp.edu.pl

2. HRR from the flammable material in a full-scale is equal to the product of the mean HRR, emitted from a surface unit obtained in small-scale test, and effective burning surface of the material.
3. The average heat flux is constant on the material's surface in the whole flame interacting area.
4. Chemical kinetics is neglected.

Generally, heat release rate in a full-scale experiment can be expressed as follows [2]:

$$\dot{Q}(t) = \int_0^t A_{\dot{Q}_{eff}}(t) \cdot \dot{q}'' \quad (1)$$

where:

$A_{\dot{Q}_{eff}}(t)$ - rate of change of the effective burning surface of the material [m²/s],

$\dot{q}''(t)$ - heat release rate per unit of burning surface, measured in cone calorimeter at time t from ignition [kW/m²].

Based on the results of Hansen^[4], Hakkarainen and Kokkali^[9], as well as Östman and Tsantaridis^[10],

it was assumed that $\dot{q}''(t) = \dot{q}''(CC)$, where

$\dot{q}''(CC)$ was a constant value, corresponding to the

average heat flux of 50 kW/m² affecting surface of the tested material. 50 kW/m² was the heat flux, at which the highest correlations of SBI and cone calorimeter methods were obtained. Effective surface of the burning material in SBI method is a function of ignition time t_{ig} determined in cone calorimeter method.

Hence, equation (1) can be rewritten as:

$$\dot{Q}(t) = \dot{q}''(CC) \int_0^t A_{\dot{Q}_{eff}} dt \quad (2)$$

It has been shown earlier^[4,5], that effective surface of the heat release in SBI test can be expressed as an exponential function of time.

Due to the same orientation of flammable material (vertical) in SBI test, this function can be expressed as:

$$A_{\dot{Q}_{eff}}(t) = a \cdot t^n \quad (3)$$

where:

a and n – fixed values, which can be obtained only by experimental correlation.

It was assumed, that the function (3) is satisfied between the beginning of ignition ($t = t_{max} \ 0$ at $\dot{Q} = 0$)

and point of achieving maximum value of HRR

$$(t = t_{max} \ \text{at} \ \dot{Q} = \dot{Q}_{max})$$

Furthermore, taking into account experiments described in^[11,12] it was assumed, that a fire growth rate

coefficient \dot{Q}_{max} / t_{max} , representing an average

increase in heat release rate during combustion of the materials oriented vertically, can be described by exponential function in the general form:

$$\dot{Q}_{max} / t_{max} = b e^l \quad (4)$$

where

b and l – constants obtained from experimental data by nonlinear regression method. l is proportional to exponent n .

Assuming that \dot{Q}_{max} / t_{max} is known, formula (4) enables to determine an exponent n .

Determination of Coefficient \dot{Q}_{max} / t_{max} : In order

to determine a general relationship between fire growth

coefficient \dot{Q}_{max} / t_{max} and thermo-physical properties

of flammable material, the main assumptions of the model of flame spread along vertical surface in Room Corner Test presented by^[2] has been adopted. In this model combustion area is a rectangle, which increases with time.

In the case of flame spreading on the surface of rigid material in a full-scale test, total HRR is a sum

of the heat rate released from fire source $\dot{Q}_s(t)$ and

heat rate released from the burning material. This statement can be written in the following mathematical form:

$$\dot{Q}(t) = \dot{Q}_s(t) + A_{fb} \dot{q}''(t) + \int_0^t \dot{q}''(t) \cdot \frac{dA_f(t)}{dt} dt \quad (5)$$

where

$\dot{Q}_s(t)$ – heat rate released from fire source [kW],

A_{fo} – initial area of thermal decomposition and combustion mainly dependant on the power of ignition source [m²],

A_f – time-variable surface of thermal decomposition and combustion [m²].

Observations of the flame spreading on a surface of material oriented vertically indicate that the surface of thermal decomposition and combustion can be expressed by the following exponent function^[2]:

$$A_f(t) = (v_y t)^k (v_x t)^m \quad (6)$$

where

v_y, v_x – components of the velocity of flame propagation in vertical and horizontal directions, respectively [m/s],

k and m - exponents,

t – time [s].

To calculate velocity of the flame front propagation, a general equation for spreading of the flame on the surface of solid thermally thin materials was applied^[13]:

$$v = \frac{\dot{q}_f'' \delta_f}{\rho \cdot c \cdot l \cdot (T_{ig} - T_0)} \quad (7)$$

where:

δ_f - length of material heating (a distance in front of the flame, where the heating of material surface from T_0 to T_{ig} occurs) by average heat flux of density

$$\dot{q}_f'' \approx 25 \text{ kW/m}^{2[14]},$$

ρ - density [kg/m³],

c - specific heat [kJ/kgK],

l - thickness of material [m],

T_{ig} - ignition temperature of material [K],

T_0 – initial temperature of material [K].

From equations (5), (6) and (7), assuming that $V_x = v_y = v$, the following formula was obtained:

$$\dot{Q}(t) = \dot{Q}_z(t) + A_{fo} \dot{q}''(t) + \left[\frac{\dot{q}_f''}{\rho \cdot c \cdot l \cdot (T_{ig} - T_0)} \right]^{k+m} \int_0^t \dot{q}''(t) \cdot \frac{d(\delta_f^{k+m} t^{k+m})}{dt} dt \quad (8)$$

Considering that after time $t = t_{max}$ HRR achieves maximum $\dot{Q}_{max}, \dot{Q}_z = \text{const}$ and product of initial surface of thermal decomposition A_{fo} and

$\dot{q}''(t)$ is a constant value, according to the

assumptions of Quintiere and Clary's model, where sum of exponents $k + m = 2$, the following relation was obtained:

$$\dot{Q}_{max} / t_{max} = A + B \left[\frac{\dot{q}_f''}{d \cdot c \cdot (T_{ig} - T_0)} \right]^2 \quad (9)$$

where:

$$A = \frac{\dot{Q}_z + A \dot{q}''(t = t_{max})}{t_{max}}$$

$$B = \dot{q}''(CC) \cdot \delta_f^2 t_{max}$$

$d = \rho \cdot l$ – surface density of material [kg/m²].

Knowing $\dot{q}''(CC)$ from cone calorimeter

method and function $A_{\dot{Q}_{eff}} = A_{\dot{Q}_{eff}}(t)$ from the correlation relations (4) and (9), function $\dot{Q} = \dot{Q}(t)$

representing HRR in a full-scale, can be determined using equations (2) and (3).

Fire Scenario – the Experimental Full Scale Data:

During the experiment, vertically oriented material, placed on the balance, with 100 cm length and 50 cm wide, was burned from the bottom side by the heat source with constant power (fig. 1). The unit was situated in the centre of ISO Room^[15] with vent (door) allowing either air inflow or exhaust outflow.

In order to mount the material vertically, metal stand placed on the silicon-calcium panel of 1 m length, 1 m wide and 12 mm thick was used. Panel density was 870 kg/m³. It was placed directly on the scale pan. A source of ignition was 130 g of heptane, poured to the steel container placed under the bottom of the sample edge (see fig. 1). Besides gas burner, this type of fire source is commonly used in SBI method. Location of the material sample was chosen to ensure approximately identical penetration of the flame on both sides of the material.

A mass loss during combustion was measured by a balance type WPT – 30S3. It has a measuring range of 30 kg and accuracy of 0.01 kg. A measurement of material sample mass was conducted to the moment, when it achieved steady value (from 600 s to 1600 s).

Assuming heat additivity, time-variable value of heat release rate was calculated from the formulas (10) – (12) as a sum of the heat released from ignition

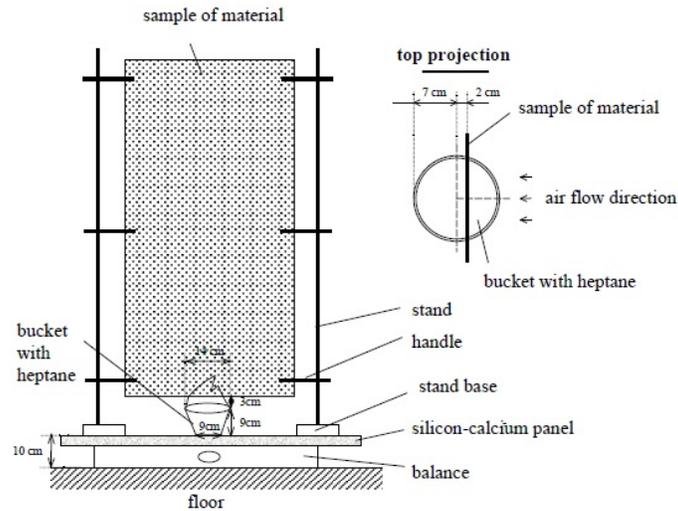


Fig. 1: A scheme of mounting of material's sample in the SBI test

source $\dot{Q}_z(t)$ and material $\dot{Q}_f(t)$

$$\dot{Q}(t) = \dot{Q}_z(t) + \dot{Q}_f(t) \quad (10)$$

$$\dot{Q}_z(t) = \dot{m}_z(t) \cdot \Delta h_{eff,z} \quad (11)$$

$$\dot{Q}_f(t) = [\dot{m}_{z+f}(t) - \dot{m}_z(t)] \cdot \Delta h_{eff,f} = \dot{m}_f(t) \cdot \Delta h_{eff,f} \quad (12)$$

where:

$\dot{m}_{z+f}(t), \dot{m}_z(t), \dot{m}_f(t)$ - mass rate of combustion of material with ignition source, only source and only material [kg/s],

$\Delta h_{eff,z}, \Delta h_{eff,f}$ - effective heat of combustion of ignition source and material obtained from small-scale method (cone calorimeter) [kJ/kg].

Mass combustion rate was directly determined during combustion full-scale processes. During the cone calorimeter experiments, changes of 5% to 20% for the average value of the effective heat of combustion of lignocellulosic materials were observed in 600 s from the ignition. In case of the other materials such as polycarbonates or sheet flooring of different compositions, the obtained changes were about 10%. Correctness of the indirect method of HRR estimation applied here was tested using validation technique of the zone fire model^[16,17].

Small Scale Data from the Cone Calorimeter:

Investigations applying cone calorimeter method were conducted according to the standard ISO 5660^[7]. This method enables to determine the rates of heat and smoke released from the materials subjected to the flux of heat radiation. Thornton's principle was used in the method. It says, that a heat generated during combustion of organic fluids and gases per unit of the mass of consumed oxygen is a constant value.

For many flammable materials such as wood, cellulosic materials, plastics, organic fluids etc. approximately 13.1 MJ of heat energy is released per 1 kg of consumed oxygen. In the most cases, deviations from this value are not higher than 5%.

The samples oriented horizontally were subjected to the flux of heat radiation, which density was equal to 50 kW/m². Such conditions correspond approximately to the end of the first phase of the fire^[18]. Uncertainty of $\dot{q}''(CC)$ and $\Delta h_{eff,f}$

obtained by this method is about 10%.

Correlation Formulas from the Experimental Data:

Taking into account relation (9) and experimental data obtained for six lignocellulosic materials, the following correlation expression can be formulated:

$$\dot{Q}_{max} / t_{max} = 6.394 \cdot 10_6 \left[\frac{\dot{q}_f''}{d.c.(T_{zg} - T_0)} \right]^2 + 2.3385 \quad (13)$$

Growing parts of the curves $\dot{Q} = \dot{Q}(t)$

determined during full-scale tests confirm the possibility of HRR expression in the form of exponent

function $\dot{Q} = at^n$ where a and n are constants. Using nonlinear regression method, the following relationship between exponent n and coefficient of fire growth has been obtained (see fig. 2).

$$n = 0.64.6 \ln(\dot{Q}_{max}/t_{max}) - 1.9399 \quad (14)$$

Using $\dot{Q}(t)$ obtained during full-scale tests for six lignocellulosic materials, function for effective heat release surface can be defined as:

$$A_{\dot{Q}_{eff}}(t) = \frac{\dot{Q}(t)}{\dot{q}''(CC)} \quad (15)$$

According to (3) above relationship was approximated for every tested material by the following exponent functions:

Porous hardboard	$A_{\dot{Q}_{eff}} = 0,00033.t^{1,63}$
Hard hardboard	$A_{\dot{Q}_{eff}} = 0,00021.t^{1,56}$
Plywood	$A_{\dot{Q}_{eff}} = 0,00146.t^{1,10}$
Chipboard	$A_{\dot{Q}_{eff}} = 0,00193.t^{0,97}$
Oakwood (wood paneling)	$A_{\dot{Q}_{eff}} = 0,00827.t^{0,83}$
Panel MDF	$A_{\dot{Q}_{eff}} = 0,03629.t^{0,33}$

Time, when $A_{\dot{Q}_{eff}}$ achieves 0.3 m^2 (this value was chosen based on the analysis of the increasing in combustion surface of selected materials) was also defined as a function of \dot{Q}_{max}/t_{max} . Its mathematical form and graphs (see fig. 3) are given below:

$$t(0,3m^2) = 14907(\dot{Q}_{max}/t_{max})^{-0.9573} \quad (16)$$

where:
 $t(0,3m^2)$ - time, when effective surface of combustion achieves 0.3 m^2 [s]. $3,0(^\circ)$

Model Validation: A validation of presented model of calculation of HRR in a full-scale from small-scale data for three lignocellulosic materials, such as panel OSB as well as chipboards with one-side and two-side laminate has been performed. Model input data and

output parameters determined by means of correlation formulas are included in table 1. To calculate coefficient \dot{Q}_{max}/t_{max} , the following input

parameters were taken: surface density of material in accordance with values given in table 1, the same for all materials constant specific heat $c = 2.51 \text{ kJ/kgK}$, average value of ignition temperature for lignocellulosic materials $T_{ig} = 360^\circ\text{C}^{[20]}$ and initial temperature of material $T_0 = 20^\circ\text{C}$. Exponent n and time $t(0.3 \text{ m}^2)$

were calculated using known value of \dot{Q}_{max}/t_{max}

and correlation equations (14) or (16), respectively. On the basis of the obtained values e.g. $n = 0.32$ and $t(0.3 \text{ m}^2) = 507 \text{ s}$ and equation (3), function

$$A_{\dot{Q}_{eff}} = A_{\dot{Q}_{eff}}(t) \text{ was defined (see tab. 1).}$$

Substituting values of $\dot{q}''(CC)$ included in table. 1 into formula (15), theoretical functions

$$\dot{Q} = \dot{Q}(t) \text{ have been defined. They were presented}$$

either in analytical form together with those determined experimentally (see tab. 2) or in graphical form in fig. 4-6.

Function $\dot{Q} = \dot{Q}(t)$ shown in fig. 4-6 describes

only a growing part of the curve within time range: from ignition to 550 s. Besides theoretical and

experimental functions $\dot{Q} = \dot{Q}(t)$ maximum \bar{E}_{max}

average \bar{E} values of relative uncertainty were included in tab. 2. According to^[21], its definitions are given below.

Maximum relative uncertainty:

$$\bar{E}_{max} = 100\% \cdot (\dot{Q}_s^{max} - \dot{Q}_m^{max}) / \dot{Q}_m^{max} \quad (17)$$

Average relative uncertainty:

$$\bar{E} = 100\% \frac{\int_{t_0}^{t_1} |\Delta \dot{Q}_s(t) - \Delta \dot{Q}_m(t)| dt}{\int_{t_0}^{t_1} \Delta \dot{Q}_m(t) dt} \quad (18)$$

where:

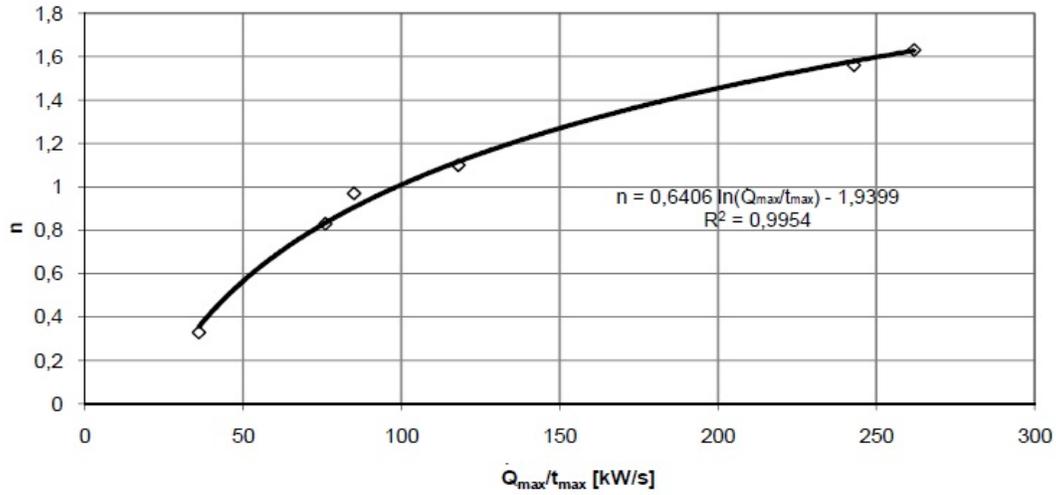


Fig. 2: Correlation relationship between n and \dot{Q}_{max}/t_{max} ¹⁹⁾.

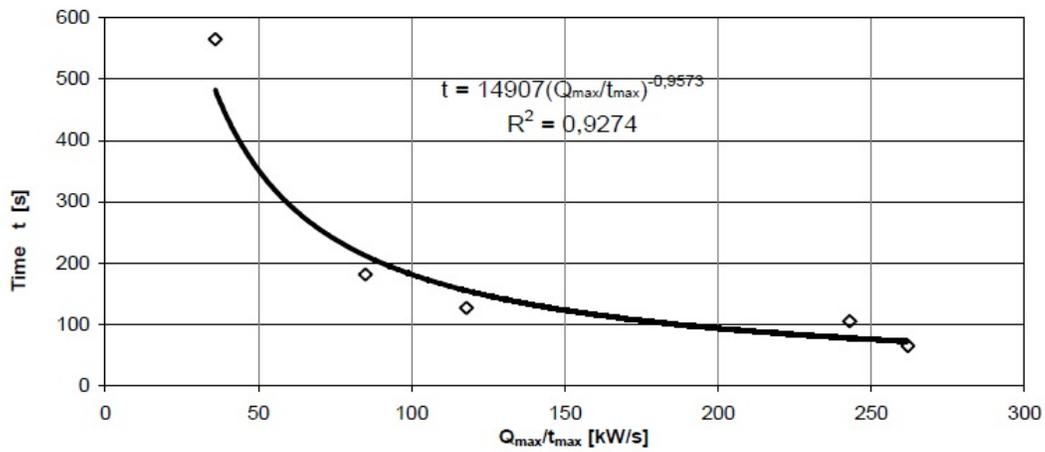


Fig. 3: Correlation relationship between $t(0,3m^2)$ and \dot{Q}_{max}/t_{max} ¹⁹⁾.

Table 1: Input, output parameters and correlation functions $A_{\dot{Q}_{eff}} = A_{\dot{Q}_{eff}}(t)$

Material	d [kg/m ²]	\dot{q}'' (CC) [kW/m ²]	\dot{Q}_{max}/t_{max} [W/s]	n [-]	$t(0,3m^2)$ [s]	$A_{\dot{Q}_{eff}} = A_{\dot{Q}_{eff}}(t)$
Panel OSB (with oriented fibres)	13.1	63.5	34.3	0.32	507	$A_{\dot{Q}_{eff}} = 0,0409 t^{0,32}$
Chipboard with one-side laminated	14.0	56.1	30.3	0.25	569	$A_{\dot{Q}_{eff}} = 0,0614 t^{0,25}$
Chipboard with both-side laminated	13.0	69.6	34.8	0.33	498	$A_{\dot{Q}_{eff}} = 0,0386 t^{0,33}$

Table 2: Theoretical (model) and experimental function $\dot{Q} = \dot{Q}(t)$ for tested materials as well as maximum \overline{E}_{max} and average relative values of uncertainty

Material	$\dot{Q}_s = \dot{Q}_s(t)$ model	$\dot{Q}_m = \dot{Q}_m(t)$ experiment	\overline{E}_{max} [%]	\overline{E} [%]
Panel OSB	$\dot{Q}_s = 2,5971t^{0,32}$	$\dot{Q}_m = 3,1591t^{0,28}$	6	3
Chipboard one-side laminated	$\dot{Q}_s = 3,4445t^{0,25}$	$\dot{Q}_m = 2,9989t^{0,29}$	12	8
Chipboard both-side laminated	$\dot{Q}_s = 2,6866t^{0,33}$	$\dot{Q}_m = 3,0956t^{0,30}$	5	3

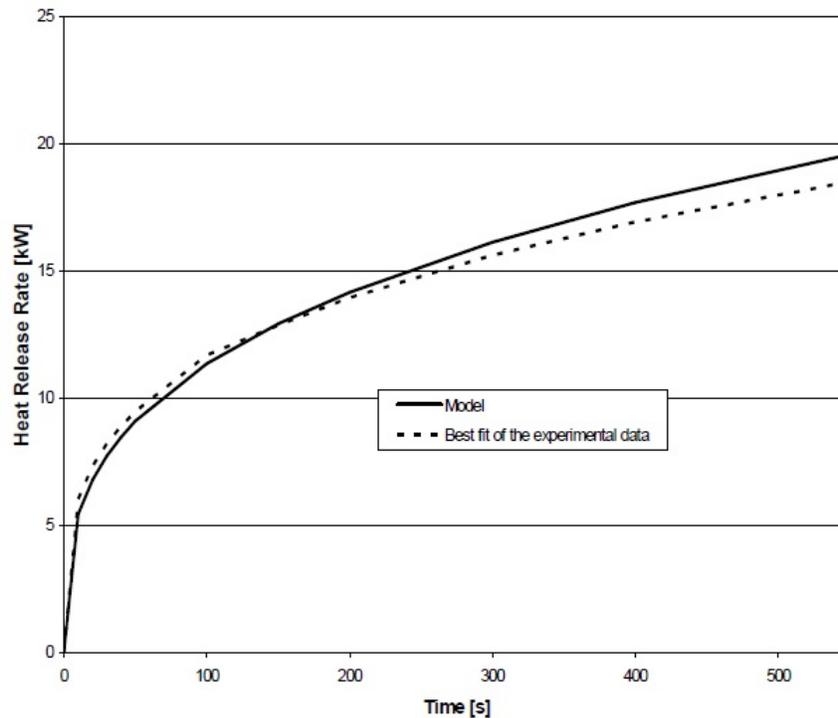


Fig. 4: HRR obtained from analytical model and experiment for panel OSB

$$\Delta \dot{Q}_s(t) = \dot{Q}_s(t) - \dot{Q}_s(0)$$

$$\Delta \dot{Q}_m(t) = \dot{Q}_m(t) - \dot{Q}_m(0)$$

t_0 - lower limit of integration – time of material ignition [s],

t_c – upper limit of integration - 550 s after ignition [s],

$\dot{Q}_s(t)$ - theoretical value of HRR after time t [kW],

$\dot{Q}_s(0)$ - initial theoretical value of HRR in the moment of ignition, equal to zero [kW],

$\dot{Q}_m(t)$ - experimental value of HRR in time t after ignition [kW],

$\dot{Q}_m(0)$ - initial experimental value of HRR in the moment of ignition, practically equal to zero [kW].

Average relative uncertainty of determination of

theoretical values of \dot{Q} changed from 3% for panel

OSB and both-side laminated chipboard to 8% for one-side laminated chipboard (see tab. 2). Arithmetic mean

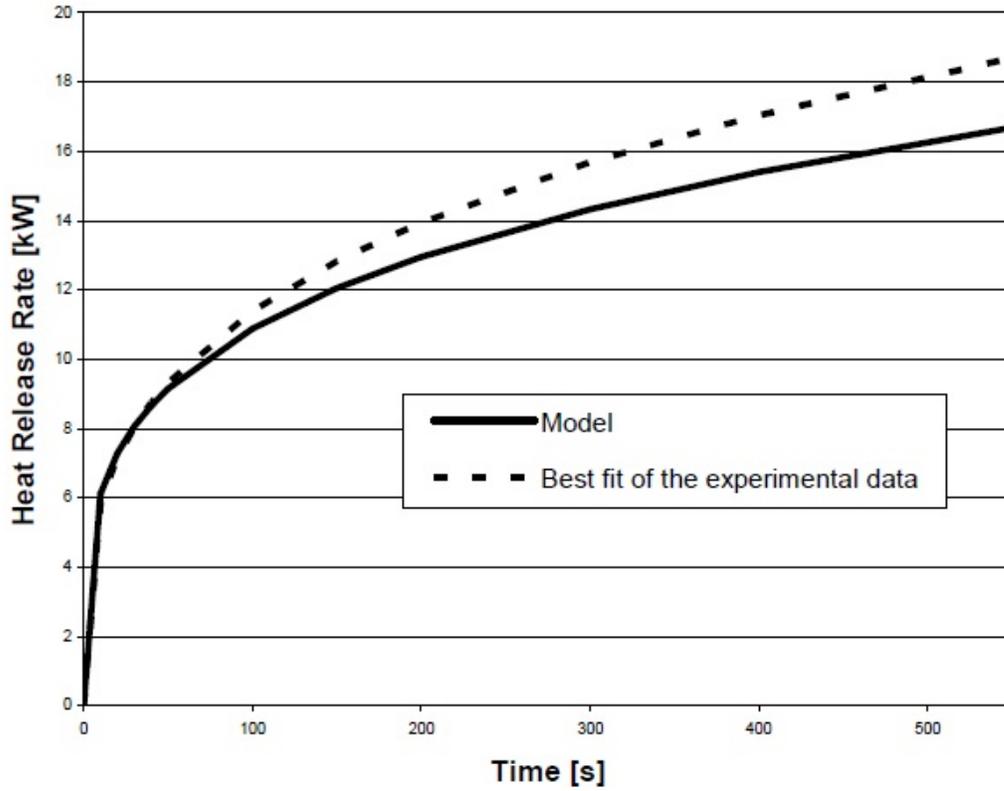


Fig. 5: HRR obtained from analytical model and experiment for chipboard one-side laminated

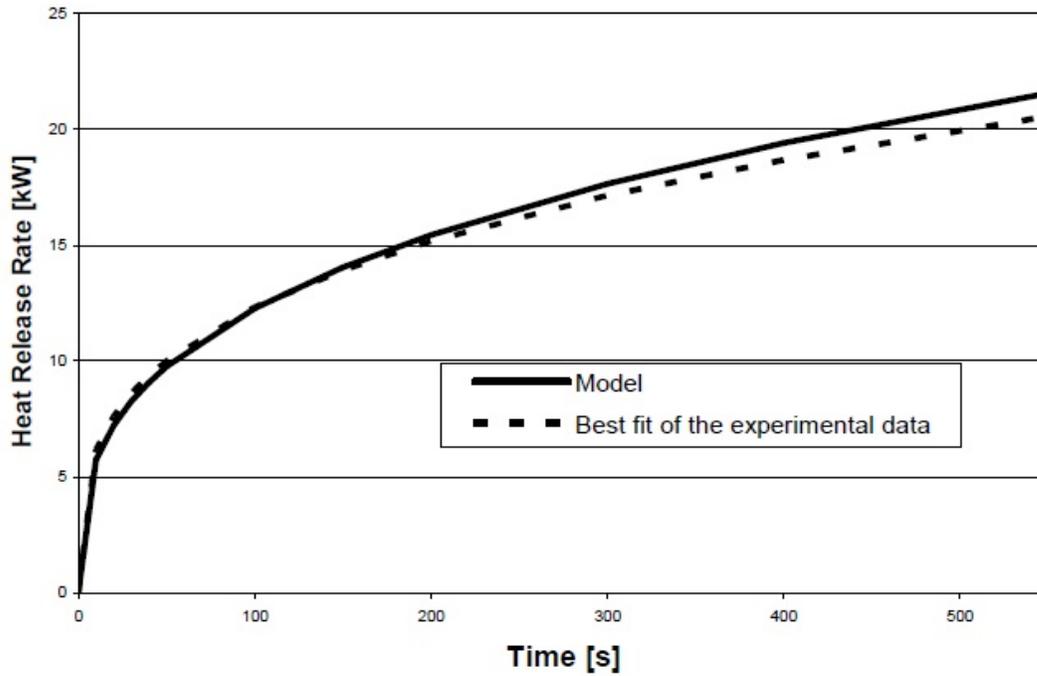


Fig. 6: HRR obtained from analytical model and experiment for chipboard both-side laminated

of the values \overline{E} , taken for all considered materials is 5%.

Application of Correlation Functions in Fire Modelling: Allowing to calculate of HRR for different flammable materials, commonly used in the buildings, correlation functions obtained experimentally enable considerable simplification of the fire modeling procedure. Substitution of the complicated calculations by simple correlation functions results in significantly shorter time of a single simulation process. The possibility of application of the functions to the SGSP zone fire model, created by Piórczyski and Gałaj^[22] and to the hybrid model currently being under construction by Gałaj and Konecki^[23] is presented below. Heat flux released during combustion is one of the main components of the right side of the equation resulting from mass and energy conservation principles in the upper layer for the zone model or in each control volume for the hybrid model.

This heat flux in both cases can be determined using the following formula:

$$\dot{Q}(t) = \sum_{i=1}^m v_{mz} \cdot F_{ci}(t) \cdot Q_{ci} \quad (19)$$

where:

v_{mz} -mass rate of combustion of i-th flammable material [kg/(m²s),

Q_{ci} -heat of combustion of i-th flammable material [kJ/s],

$F_{ci}(t)$ - time-variable surface of combustion of i-th material, which can be calculated by the method given in^[22].

Now a previously described complicated procedure of heat flux determination can be substituted by a considerably simpler calculation procedure, which algorithm consists of the following points:

1. A selection of the appropriate theoretical function $\dot{Q}_s(t)$ included in tab. 2 for the material, which thermal properties are closely compatible with one of the tested material.
2. Substituting 0 for t (time).
3. Increment a time by integration step Δt .
4.

5. Calculation of $\dot{Q}(t) = \dot{Q}_s(t)$ for a current time t using the selected correlation function.
6. Inserting of the value calculated in point 5. into the right side of the mass and energy conservation equations.
7. Execution of integration procedure to obtain the fire parameters (temperature, concentrations of species etc.) for current time t
8.
9. Checking if a current time t exceeds assumed time of simulation.
10. If not, then return to point 3. Otherwise, simulation procedure is finished.

Performing a validation of the fire model with simplified procedure of heat flux calculation, potential differences between thermal properties of the specific material and selected lignocellulosic material, for which correlation function has been defined, should be taken into account.

Conclusions: A presented model, which is based on the conception of effective surface of heat release and experimental correlations, allows to calculate heat release rate during combustion of lignocellulosic materials in a full-scale test using data obtained from small-scale test with cone calorimeter. The proposed model is simpler than models with the comparable uncertainty described in the literature. Disadvantages of the model are limitation of experiments only to several lignocellulosic materials and one scenario of the fire in the compartment. Obtaining experimental correlations for other materials such as finishing (e.g. lining) and furnishing materials was not succeeded because of the great differences between its composition and spatial orientation.

A described procedure can be applied to calculation of HRR in a full-scale for a group of materials, which chemical composition as well as thermal and flow properties are very similar to the tested materials. An example of utilizing of proposed procedure was given for the zone and the hybrid fire models.

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